ADVANCED PROPULSION FOR SMALL BODY MISSIONS PART 2

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Part 2 Agenda

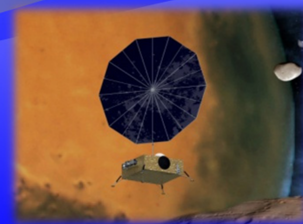
1. Flight applications to date
2. Future driving requirements and associated mission applications and capabilities provided by this technology
3. Specific mission examples of the application of near-term and longer-term propulsion options

Flight Applications to Date

SEP trajectories bring dramatic improvements to science missions

Multiple rendezvous for small bodies

- Enables many asteroid and comet missions that would be impractical without SEP



Control of arrival conditions

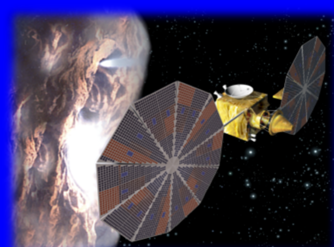
- Achieve lower speed arrival or control arrival time for Mars or Venus entry
- Change direction and velocity of approach to reach more landing sites

Reduced number of mission critical events

- e.g., orbit insertion, earth avoidance, response to anomalies……

More mass delivered to destination

- Could enable more mass on smaller (and cheaper) launch vehicles
- Provides performance margin and resilience to mass growth



More flexible launch opportunities

- More frequent launch opportunities
  - e.g., Dawn delay was possible to accommodate Phoenix launch
- Decreased reliance on JGA availability

Shorter trip times

- Might expand feasible mission set beyond the asteroid belt including return of samples to Earth

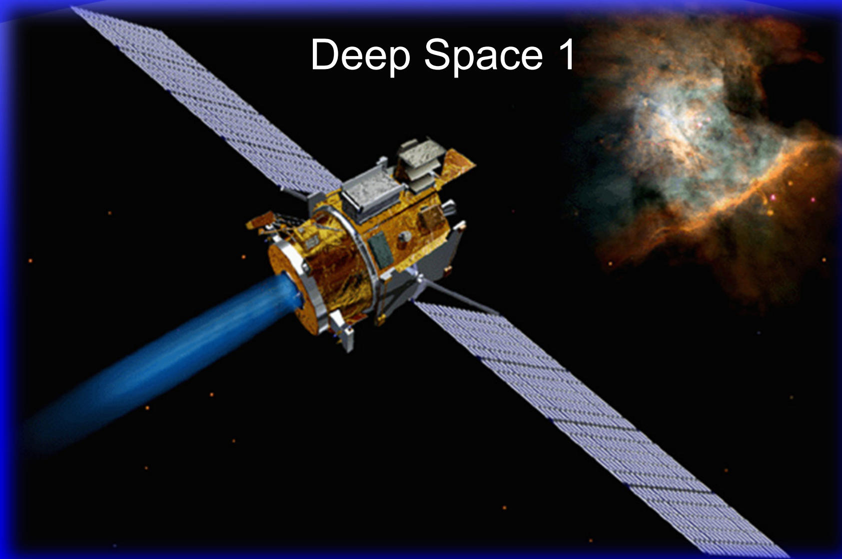
SEP Has Been Used on Two NASA Deep Space Missions – So Far

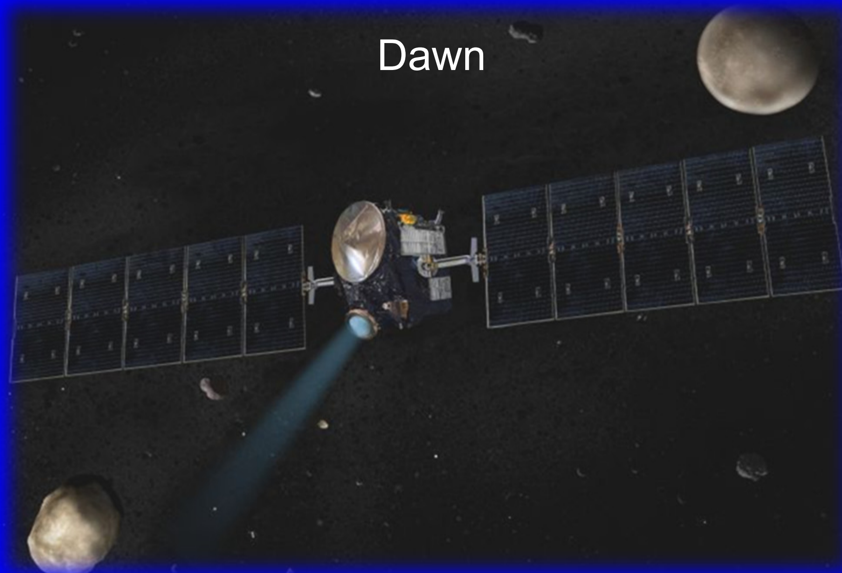
Deep Space 1:

- Technology Demonstration Mission
- Retired the following risks:
  - Thruster life
  - Guidance, navigation and control of an SEP spacecraft
  - Mission operations Costs
  - Spacecraft contamination
  - Communications impact
  - Electromagnetic compatibility

Dawn:

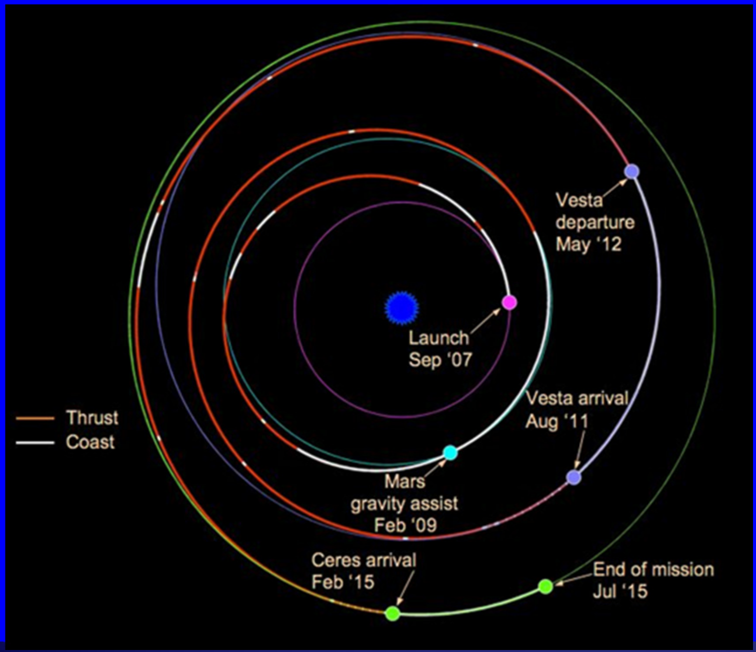
- **The use of SEP on Dawn reduced the cost of a multiple main belt asteroid rendezvous mission from New Frontier-class to Discovery-class – a difference of over $200M**





Current Status: Dawn

- Will orbit **both** the main-belt asteroid Vesta and the dwarf planet Ceres
- Launched: September 2007
- 1218 kg launch mass (dry mass of 750 kg)
- 10-kW Solar Array (at 1 AU)
- **20,000 hours of thrusting with the ion propulsion system and operating flawlessly**
  - Approximate ΔV delivered to date: 5.7 km/s
  - Xenon used to date: 212 kg
- July 2011 arrival at Vesta



Current Status: International

SMART-1: Small Mission for Advanced Research in Technology

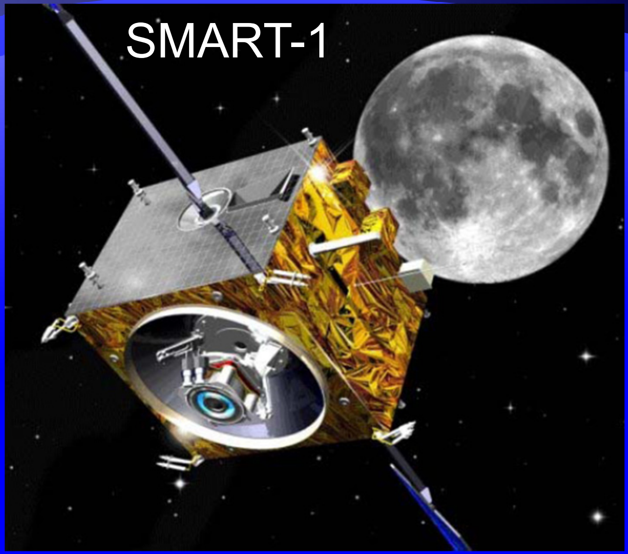
- Launched: September 2003

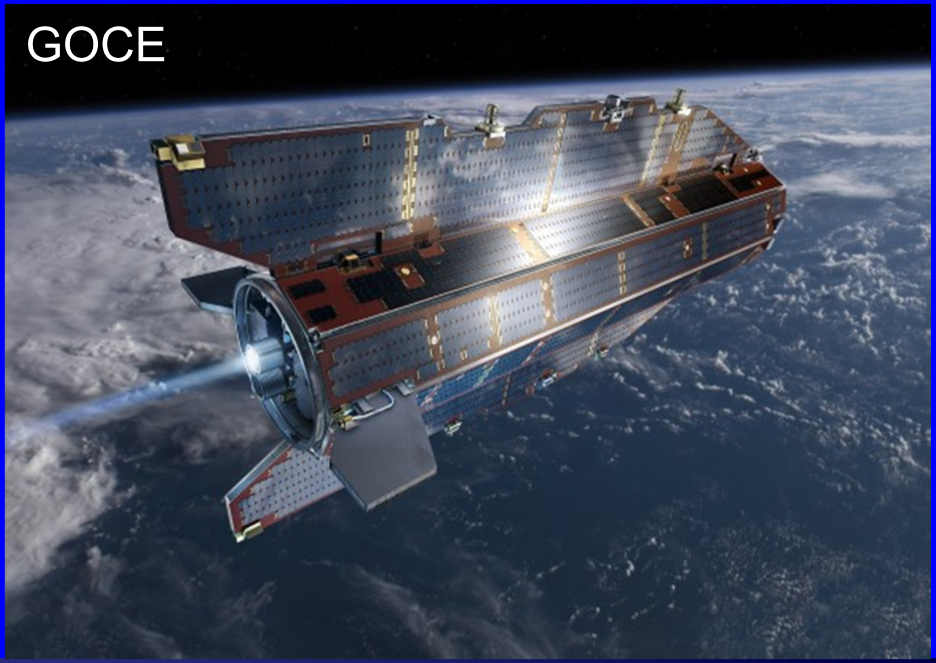
Hayabusa: Near-earth asteroid sample return

- Launched: May 2003
- Return: June 13, 2010

GOCE: Gravity field and steady-state Ocean Circulation Explorer

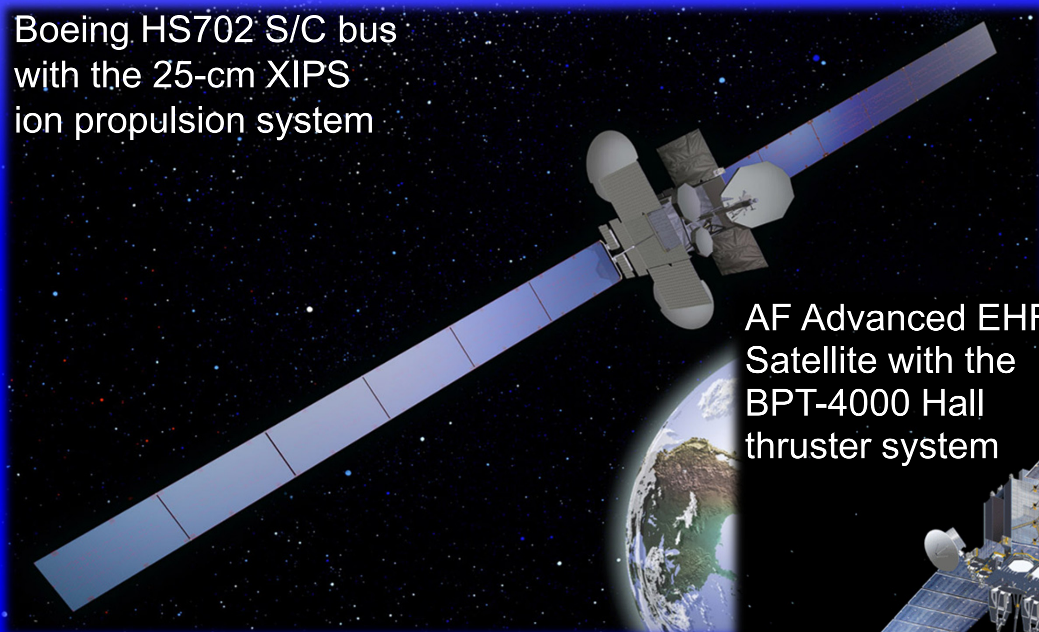
- Launched: March 2009



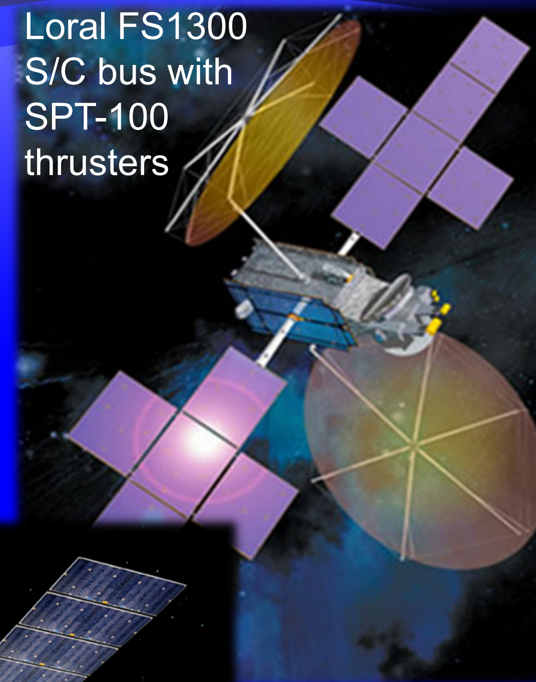


Current Status: Commercial

- **53 commercial satellites** now flying with xenon ion propulsion
- Commercial satellites now flying with up to **24 kW** of solar power at beginning of life



Boeing HS702 S/C bus with the 25-cm XIPS ion propulsion system



Loral FS1300 S/C bus with SPT-100 thrusters

AF Advanced EHF Satellite with the BPT-4000 Hall thruster system

- **High power (> 20 kW) is now routine on commercial satellites**
- **Electric propulsion now used by almost all major satellite providers because it provides a significant economic benefit to the end user**

Driving Requirements

Primitive Body Missions (examples only)

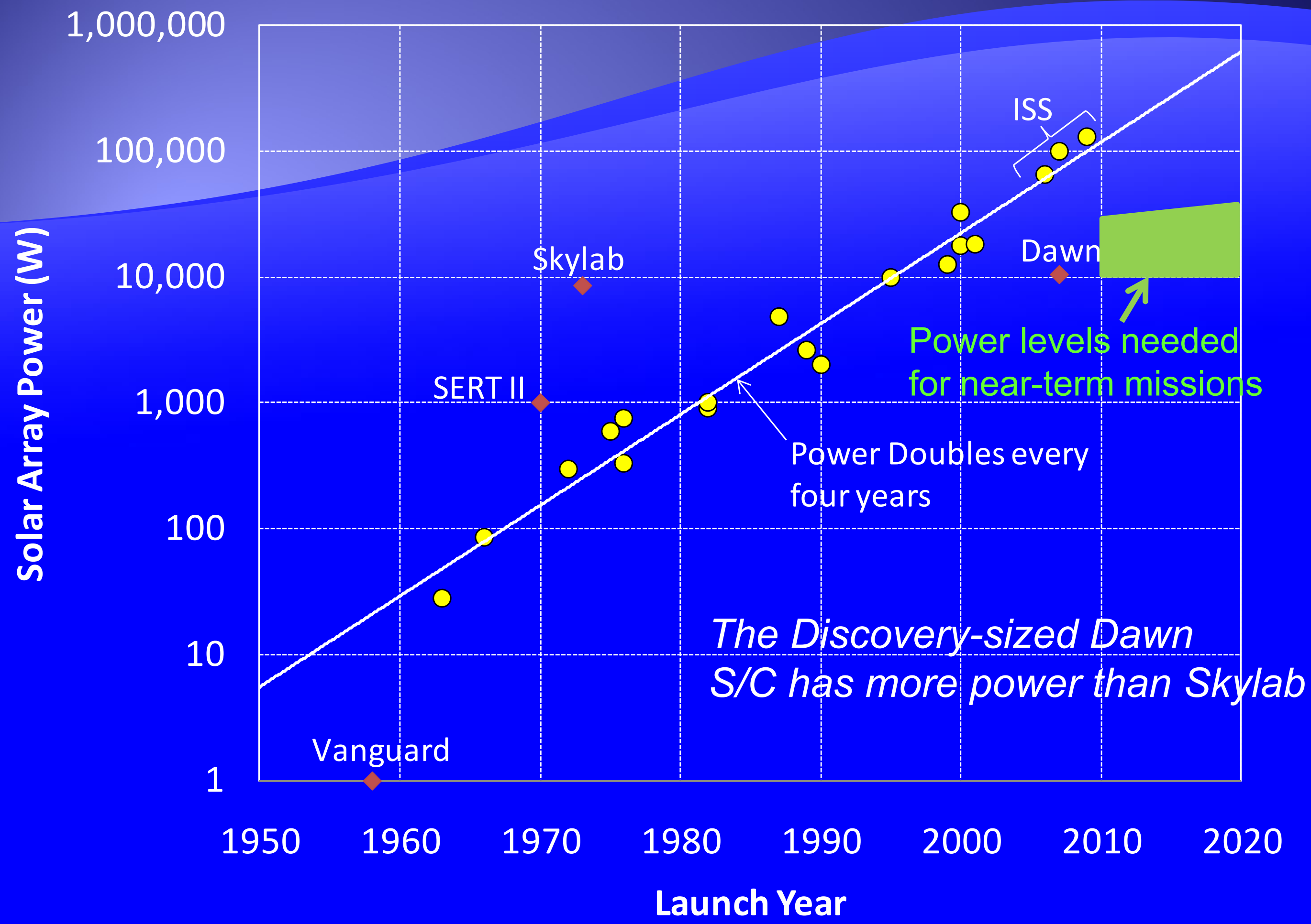
- Low-mass body rendezvous
- Multiple flybys of NEOs, e.g., flyby 39 NEOs in 10 years with SEP
- Sample return missions from primitive bodies

Target	Mission	Flight Time (years)	Power	Benefit
Near Earth Objects (0.98 to 1.3 AU)	• Sample Return • Multiple Flybys	< 4 10	Solar: 5 to 15 kW	Increases number of reachable objects from a few dozen to thousands
Jupiter Family Comets (1 to 6 AU)	• Rendezvous • Sample Return	3 to 5 9 (round trip)	Solar: 10 to 15 kW Solar: 15 to 30 kW	Enables missions to large, hard-to-reach comets (Tempel 1, 2, etc.)
Main Belt Asteroids (1.7 to 5 AU)	• Multiple Rendezvous	~4 (per object)	Solar: 10 to 15 kW	Enables multiple main-belt asteroid rendezvous missions
Trojan Asteroids (~5 AU)	• Rendezvous	3 - 5	Solar: 30 kW RPS*: ~1 kW	Enables rendezvous missions
Centaurs (5 to 30 AU)	• Rendezvous	9 - 10	RPS: ~1 kW	Enables rendezvous missions
Kuiper Belt Objects (> 40 AU)	• Multiple Flybys • Rendezvous	10 - 20	RPS: ~1 kW	Enables rendezvous missions

*Radioisotope Power System at ~8 W/kg

➢ **Electric propulsion greatly expands the number of reachable target bodies for affordable primitive body missions.**

Solar Array Technology Status



- **Maximum solar power per spacecraft has doubled approximately every 4 years for the last 50 years.**
- **Power levels needed for deep-space missions are now routine, but light-weight, low-risk arrays are required to improve performance**

Advanced Solar Arrays: What's Needed

- Primary Drivers
  - Power Level
  - Cost
  - Risk (real and perceived)
  - Specific Power (W/kg)
- Secondary Drivers
  - Low Intensity Low Temp. (LILT)
  - Natural Frequency
  - Packaging
  - High-temperature operation (for Venus gravity assist trajectories)

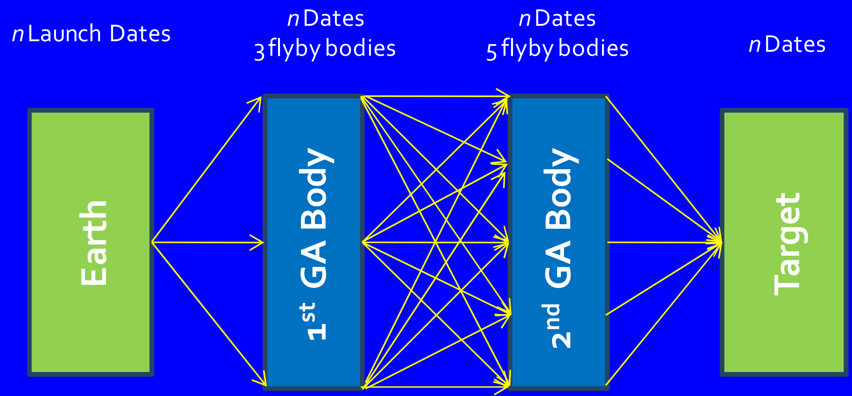
Mission	BOL Power (kW)	Specific Power (W/kg)	Specific Cost ($/W)
DS1 (1998)	2.5	42	"free"
Dawn (2007)	10.3	82	~900
Near-Term	10 to 30	> 200	< 500
Far-Term	> 100	> 300	< 250

- ISS arrays are about 27 W/kg and $3,500/W

➢ **Need low-risk, light-weight solar arrays in the 10- to 30-kW range.**
➢ **At 30 kW, a 200W/kg array saves > 200kg relative to an 82 W/kg array.**

Low-Thrust Trajectory Analysis Capability

- SEP combined with multiple gravity assist flybys is a powerful combination for outer planet missions, but the vast number of possible combinations can make it a daunting task to find the good trajectories
- The number of possible trajectories grows geometrically with the number of encounters



For n = 12 there are 12 x (3 x 12) x (5 x 12) x 12 = 311,040 trajectories

- Deep Space 1 had no gravity assists
- Dawn uses a single Mars gravity assist
- The Titan Saturn System Mission study considered the following trajectory options
  - Earth-Earth-Venus-Venus-Earth-Saturn
  - Earth-Venus-Venus-Earth-Saturn
  - Earth-Earth-Earth-Saturn
  - Earth-Mars-Venus-Earth-Saturn
  - Earth-Venus-Earth-Earth-Saturn

➢ **Advanced trajectory analysis capabilities are required to find the best low-thrust trajectories, which are mission enhancing and in some cases mission enabling.**

EP Technology: What's Needed

Flagship and New Frontier Missions

- Solar Array Power Levels of 15- to 30 kW
- Primary Drivers (per thruster)
  - Life (Propellant Throughput): > 900 kg
  - Power: 5 kW to > 10 kW
  - Specific Impulse: > 4,000 s
  - Throttle Range: 30-to-1
  - Affordable PPU

Discovery Missions

- Solar Array Power Levels of 5- to 15 kW
- Primary Drivers (per thruster)
  - Life (Propellant Throughput): > 450 kg
  - Power: 3 kW to 5 kW
  - Specific Impulse: 2,500 to 3,500 s
  - Throttle Range: 15-to-1
  - Affordable PPU

- *Thruster life limitations forced Dawn to carry 3 thrusters cross-strapped to 2 PPUs – an expensive arrangement*
- *The simplest, lowest-cost electric propulsion system would have just two thrusters – one primary and one spare. To achieve this, high-power, long-life thruster development is needed for missions with power levels > ~15 kW*

> **Need high-power thrusters for directed missions**
> **Need low-cost, low-risk electric propulsion systems for competed missions**

Current Status: Ongoing Technology Development

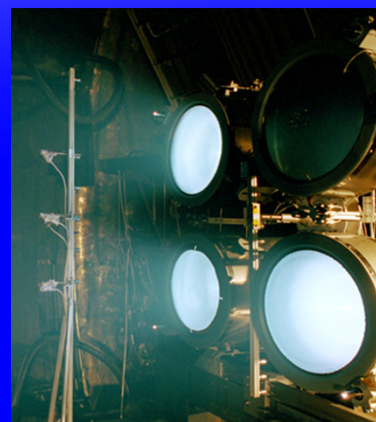
Ongoing Technology Development: NEXT

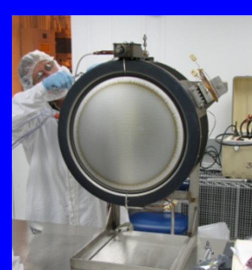
NEXT is the right size for near-term New Frontiers mission candidates

Thruster Attribute	NEXT
Max. Input Power, kW	Up to 6.9
Throttle Range	>12:1
Max. Specific Impulse, s	4,190
Efficiency @ Full Power	71%
Propellant Throughput, kg (with 1.5 qual factor)	>300 (design) 500 (projected)
Specific Mass, kg/kW	1.8
PPU Attribute	
Input voltage (from s/c), V	80-160
Mass, kg	33.9

Technical Status	TRL
NEXT Components	
Thruster	**6**
Power Processor Unit	**4-5**
Xenon Feed System	**6**
Gimbal	**4-5**
NEXT-related Components	
Standard Arch DCIU	**3**

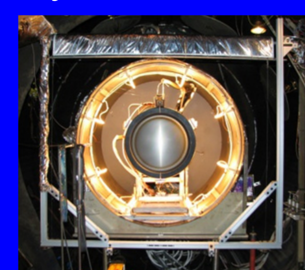
Investments to Date	$45M
Cost to TRL6	$15M to 18M





FY10 funded key activities ($2.5M):
- PPU re-verification test
- Residual System Integration Test
- PPU environmental test
- Long-Duration Test (LDT)
- Phase II Review
- Technology Maturation Review

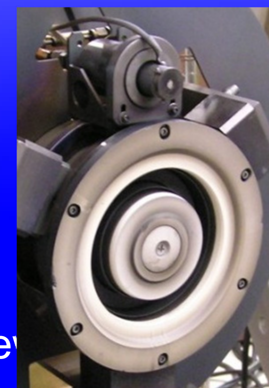
FY11-13 funded key activities ($6.5M):
- PPU design iteration and/or DCIU maturation
- LDT extension to demo 750 kg
- Residual, high-priority risk reduction activities



Current Status: Ongoing Technology Development

Ongoing Technology Development: High-Isp Hall

High-Isp Hall thrusters needed for expanded mission capture



Thruster Attribute	High-Isp (HIVHAC) Hall
Input Power	0.3 - 3.5 kW
Specific Impulse	1600 - 2700 s
Efficiency	> 55% @ 3.5 kW
Thrust	20 – 150 mN
Propellant Throughput	> 300 kg
Specific Mass	2.4 kg/kW
Operational Life	> 10,000 hrs
PPU Attribute	
Input voltage (from s/c)	80-160 V

Technical Status	TRL
HIVHAC Components	
Thruster	**3-4**
HIVHAC-related Components	
Power Processor Unit	**3**
Xenon Feed System	**6**
Gimbal	**4-5**

Investments to Date	$4M
Cost to TRL6	$14M to $16M

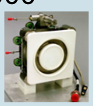
<u>FY10 planned key activities ($1M):</u>

- EM thruster performance test
- EM thruster environmental test
- Long Duration Test Readiness Revie
- Hall-related component evaluation
- System study of BPT-4000 thruster option(s)
  - “Higher Isp” option vs. “as-sold” option

<u>FY11-15 planned key activities ($4M):</u>

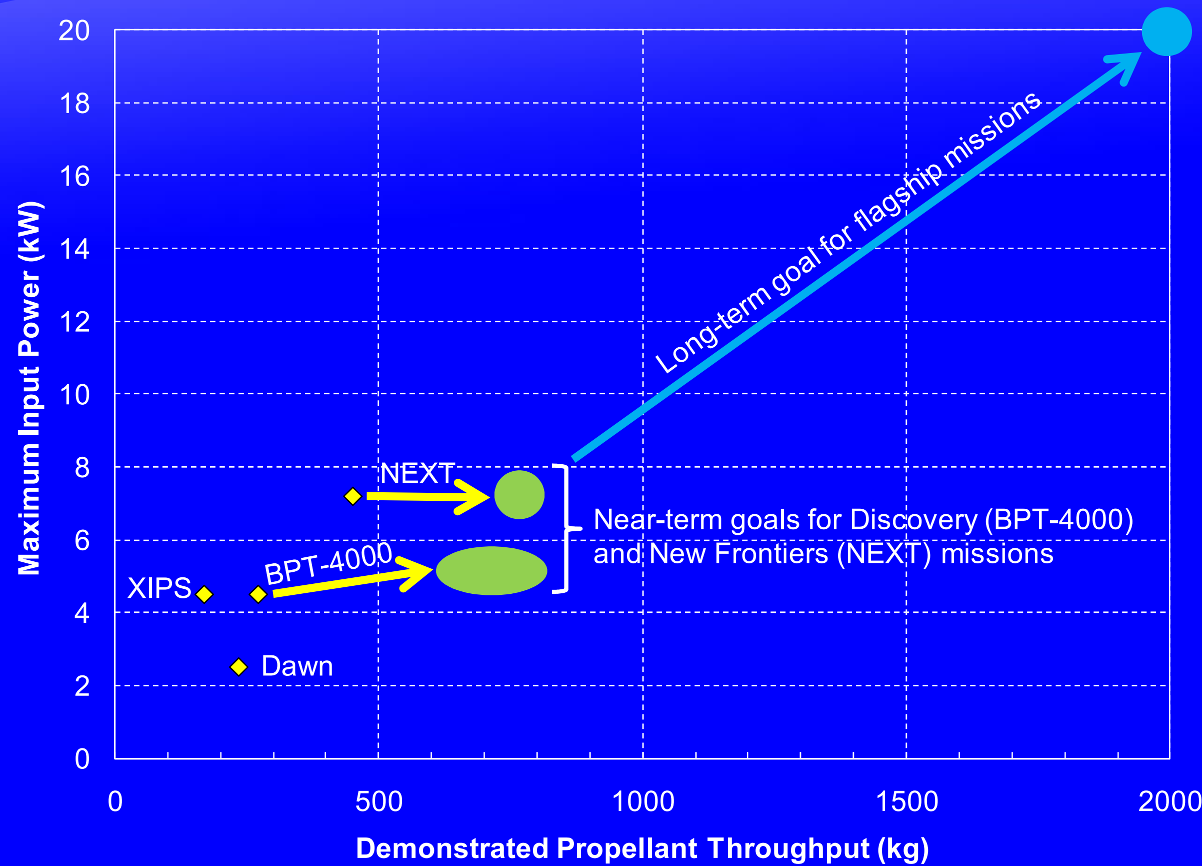
- Component development for remaining system: PPU, feed system, etc.
- System integration
- Life testing

Capability Gaps

Electric Propulsion Technology	TRL	Demonstrated Performance	Gap	Benefit of Filling the Gap
NSTAR /Dawn 	9	Max. Power: 2.5 kW Max. Isp: 3100 s Throughput: 235 kg	1. PPU too expensive due to manufacturablility problems	1. This technology has been overtaken by more modern versions (i.e., NEXT)
XIPS 	9	Max. Power: 4.5 kW Max. Isp: 3500 s Throughput: 170 kg	1. Demonstrated propellant throughput of 170 kg is too low for most missions 2. PPU modifications required for deep-space missions	1. NEXT throughput capability makes redoing the XIPS life test questionable 2. PPU could be modified to operate the NEXT thruster resulting in significant cost savings
BPT-4000 	7	Max. Power: 4.5 kW Max. Isp: 2000 s Throughput: 272 kg	1. PPU redesign needed for deep-space missions 2. Demonstrated propellant throughput of 272 kg is too low for some missions, need > 600 kg 3. Isp of 2000s is too low for many missions, need ~2800 s	1. Lowest cost EP system for projected Discovery and NF missions 2. Would reduce system cost and complexity for many missions 3. Increase mission capture to all near-term competed missions
NEXT 	4	Max. Power: 7.2 kW Max. Isp: 4200 s Throughput: 450 kg	1. Too expensive for competed missions • PPU difficult to manufacture and troubleshoot • Significant PPU development issues remain • Digital Interface and Control Unit requires significant development 2. Power too low for far-term missions	1. Repackaging required to fix technical issues, improve manufacturability, and reach TRL6 in order to lower cost and risk to acceptable levels 2. Would reduce EP system complexity and cost for far-term missions
HIVHAC 	3	Max. Power: 3.5 kW Max. Isp: 2700 s Throughput: TBD kg	1. PPU needed for deep-space missions 2. Significant life issues remain	1. Same PPU could also be used with the BPT-4000 2. High propellant throughput capability essential for mission capture

Capability Gaps

- Meeting the near-term goals is necessary to reduce cost and risk for potential Discovery and New Frontiers users
- Long-term goal represents an order of magnitude increase in power and propellant throughput relative to the Dawn ion thruster
- Meeting the long-term goals is necessary to enable exciting new mission possibilities



Thruster Technology Needed for Flagship / New Frontiers Missions

Thruster	Maximum Input Power (kW)	Projected Propellant Throughput (kg)	Maximum Isp (s)	Current TRL	Time to TRL6
NEXT	7.2	750	4200	6	Near Term: ≤ 3 years
NEXT STEP	13.7	750	4400	4	Mid Term: ≤ 6 years
High-Power Hall	20	2000	3000	4	Mid Term: ≤ 6 years
High-Power Ion	28	2000	8500	3	Far Term: ≤ 9 years

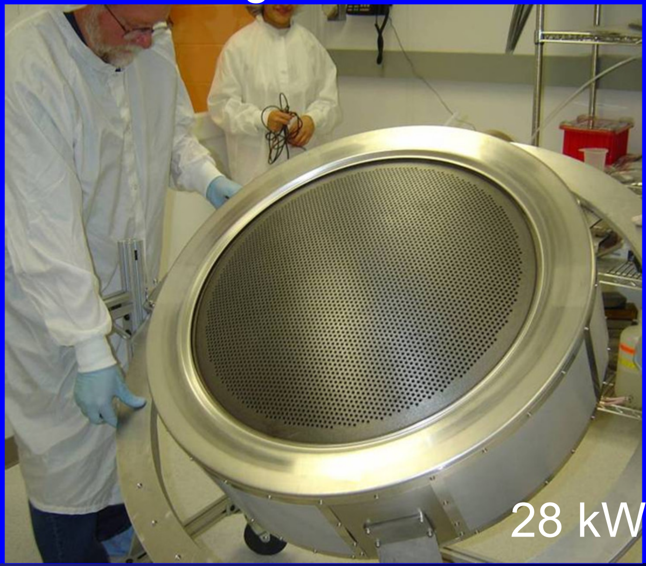
NEXT/NEXT STEP

7.2 – 13.7 kW

High-Power Hall

20 kW

High-Power Ion

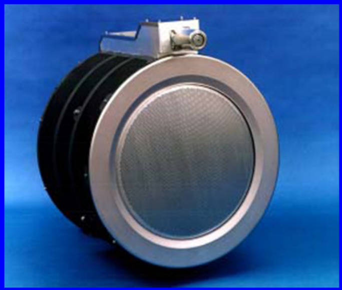


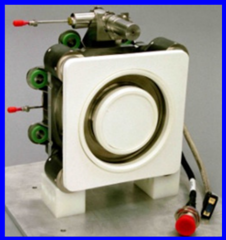
28 kW

- **It is now possible to build EP thrusters with capabilities that were unheard of only a few years ago enabling new mission concepts.**

Thrusters Technology Needed for Discovery Missions

Thruster	Maximum Input Power (kW)	Demonstrated Propellant Throughput (kg)	Demonstrated Maximum Isp (s)	Current TRL	Time to TRL6
NSTAR/Dawn	2.5	235	3100	9	N/A
XIPS	4.5	155	3500	9	N/A
BPT-4000 Hall	4.5	272	2200	7	Near Term: ≤ 3 years
NEXT	7.2	450	4200	5	Near Term: ≤ 3 years
High-Isp Hall	4.5	---	2800	4	Mid Term: ≤ 6 years





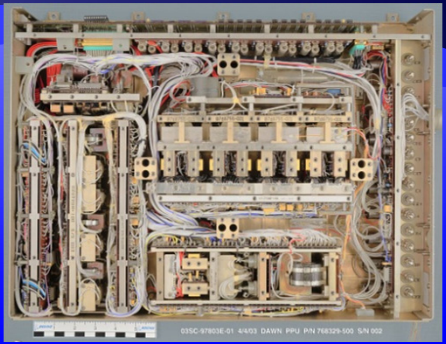
NSTAR/Dawn XIPS NEXT BPT-4000

➢ **For near-term Discovery missions available thrusters have excellent performance, but the power processor units (PPU) are problematical.**

What's Needed: Power Processors

- Power Processor Unit (PPU)
  - Converts the solar array power to the currents and voltages needed to start and operate the thruster
  - **PPUs are complicated and expensive**
- Commercial PPUs are designed to operate from a regulated high-voltage bus
- PPUs for deep-space missions must accept a variable input voltage (typically 80 V to 140 V)
- A modular PPU design (like XIPS) is needed to improve manufacturability and enable tailoring for different power levels

Dawn



NEXT

XIPS

➢ **Need a modular PPU that is manufacturable and affordable to improve mission capture for competed missions.**

Specific mission example

Asteroid Return Mission Feasibility Study

What?

- Identify a very small Near Earth Asteroid (NEA) with a mass of ~10,000 kg (corresponding to a diameter of ~2 m)
- Use a high-power Solar Electric Propulsion (SEP) System to rendezvous with this object, capture it, and return it to the International Space Station (ISS)

When?

- Launch before the end of the decade using a single evolved expendable launch vehicle (EELV) with a total flight time of ~5years

Why?

- Assess resource potential of NEAs for exploration and commercial use
- Use the ISS as a geology lab
- Use the ISS as a test bed for learning how to handle/process asteroid material in space

Relative size of a ~10,000-kg NEA and an astronaut

Is It Feasible to Capture and Return a NEA to the ISS?

Key Feasibility Issues:

- Is it possible to find a sufficiently small, scientifically interesting NEA in an accessible orbit?
- How would you capture, secure, and transport a 10,000-kg asteroid?
- How would you safely approach and dock with the ISS while transporting a 10,000-kg asteroid?
- What would you do with a 10,000-kg asteroid at the ISS?

The asteroid would be curated at ISS where numerous possible scientific and resource utilization experiments would be conducted. Sampling and packaging would be done by astronauts on EVA, analogous to lunar sampling during Apollo. This would provide valuable experience with tools and techniques, prior to the human mission to a NEA.

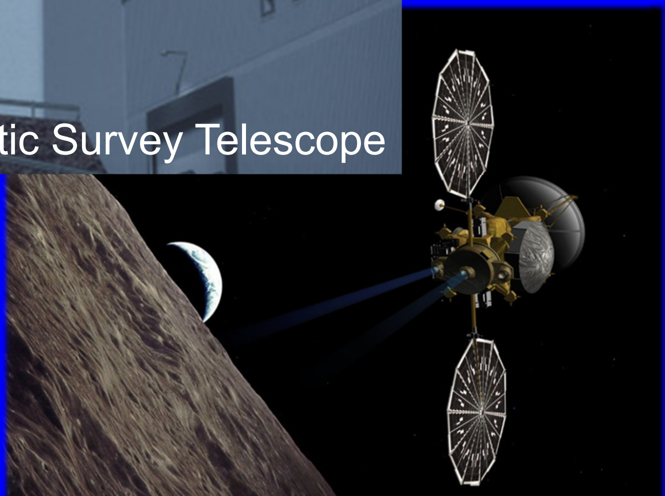
Yes! It Appears to be Feasible to Rendezvous with, Capture, and Return an Entire NEA to the ISS

- Reasonable projections suggest that several dozen candidate NEAs of the right size and orbit could be found through the use of new telescopes by the end of the decade from which a suitable target could be selected.
- Low-thrust trajectory analyses suggest that the mission could be performed from a single EELV with a total flight time of approximately 5 years and a SEP power level of 40 kW.
- A concept for capturing, securing, and despinning the asteroid has been identified.
- Multiple approaches for docking the SEP vehicle and its asteroid cargo with the ISS have been identified.
- Safely handling the asteroid at the ISS would require care and planning, but is definitely feasible.
- Planetary protection issues were not addressed in this study.

Pan-STARRS

The Panoramic Survey Telescope & Rapid Response System

Large Synoptic Survey Telescope



High-Power Electric Propulsion

SEP Recommendations

- Complete NEXT to TRL6 for near-term New Frontiers and Flagship missions
- Complete High-Isp Hall development for Discovery missions
- Develop high-power, very-long-life, electric propulsion technologies for far-term New Frontiers and flagship missions
- Develop advanced trajectory techniques needed to find the best performing low-thrust trajectories from among millions of possible combinations
- Develop thruster life validation modeling and simulations necessary for risk management of EP system implementation